Microfabrication of a mechanically controllable break junction in silicon

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We present a detailed description of the fabrication and operation at room temperature of a novel type of tunnel displacement transducer. Instead of a feedback system it relies on a large reduction factor assuring an inherently stable device. Stability measurements in the tunnel regime infer an electrode stability within 3 pm in a 1 kHz bandwidth. In the contact regime the conductance takes on a discrete number of values when the constriction is reduced atom by atom. This reflects the conduction through discrete channels. © *1995 American Institute of Physics.*

Micromachining in silicon is an ongoing effort to provide ever smaller devices used as the active part of a sensor. Currently, it is straightforward to produce suspended beams, small springs, and vibrating or rotating structures on a chip. Engineers can make use of a number of classical transducer phenomena, such as piezoelectricity, piezoresistivity and capacitance changes to convert displacements into an electrical signal. However, the formation of smaller sensors is often obtained at the cost of precision, since the signal of the above mentioned transducer phenomena scale with size. In contrast to classical transducers, a tunnel transducer[1] (e.g., an STM) is compatible with further miniaturization and possesses an astonishing sensitivity to displacements. When a vacuum tunnel gap between two metallic electrodes is increased by 1 Å, the tunnel resistance increases approximately by an order of magnitude. This has been realized by a number of groups who have used tunnel sensors in devices.[2] The extreme sensitivity of these sensors on positional displacements however implies that the practical range of operation is limited to distances smaller than 5 Å since at larger distances the resistance becomes almost infinite and unmeasurable.

In conventional STM embodiments, one electrode is usually mounted on a flexible lever, which can be moved by an electrical signal. The tunnel gap is kept constant with the use of a feedback system, necessary since temperature fluctuations, (acoustic) vibrations or other disturbances will otherwise change the vacuum gap over distances much larger than the practical range. An accelerometer, magnetometer, and an infrared sensor have been successfully developed with these kind of tunnel sensors in feedback operation.[2] Despite these successes we have used a different approach and constructed an inherently stable tunnel sensor. When used as a displacement sensor this device can be fabricated in such a way that the electrode separation during operation remains in the practical range of about 5 Å. Due to the extreme stability of this device it can be operated without feedback; however it may also be used in a feedback loop. In this letter we present the fabrication and operation of this new type of tunnel sensor which was proposed in Ref. 3. It is inherently stable, adjustable, and compatible with silicon technology. Detailed measurements are shown, in both the contact and tunnel regimes.

The principle of operation and a schematic perspective and cross sectional view of the device are shown in Fig. 1. The starting material is a $\langle 100 \rangle$ oriented 250 μm thick silicon wafer with an oxide layer of 400 nm. Standard electron-beam lithography is used to define a pattern in a PMMA bilayer used for the evaporation of an adhesion layer (10 Å Ti) and 800 Å of gold onto the oxide. The gold film has a shape as indicated in Fig. 1(a). Next a photolithographically defined thick layer of aluminum is evaporated everywhere on the oxide except over a distance u, centered around the smallest gold feature. The next step uses the gold and alumi-
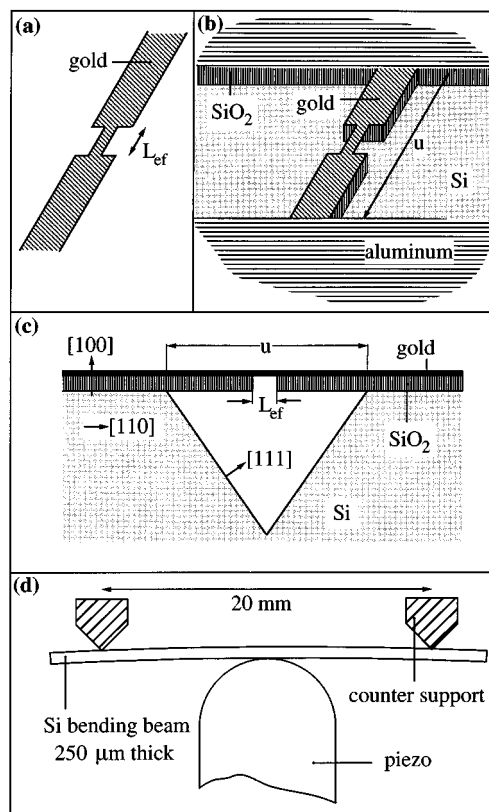

FIG. 1. (a) The gold wire defined by electron-beam lithography. The smallest width of the wire is 100 nm, L_{eff} is about 250 nm. (b) Both the aluminum and gold film are used as an etch mask to etch through the SiO_2 into the Si. (c) A cross section along the gold wire after the pit is etched into the silicon. Si etching is stopped at the concave corners and the intersection between the $\langle 111 \rangle$ crystallographic surface and the SiO_2 edges. (d) The mounting configuration of the silicon bending beam in a break junction setup.

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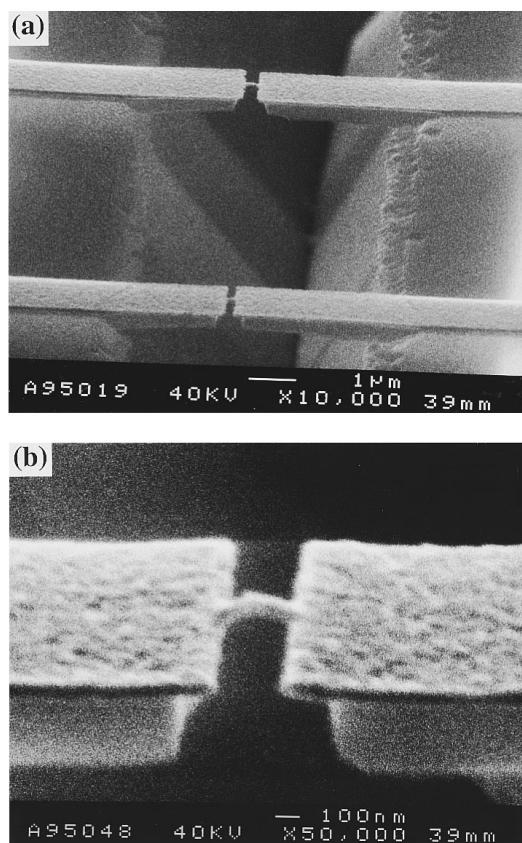| 16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
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FIG. 2. (a) Two devices suspended above a triangular pit in the Si substrate before the connecting wire is broken in the break junction setup. Each device shows two SiO_2 cantilevers which are covered and bridged by the gold wire. (b) A close-up showing the connecting wire. Before operating the device in the contact or tunnel regime the small connecting wire has to be broken. Some undercut of the gold is present due to the imperfection of the reactive ion etching process.
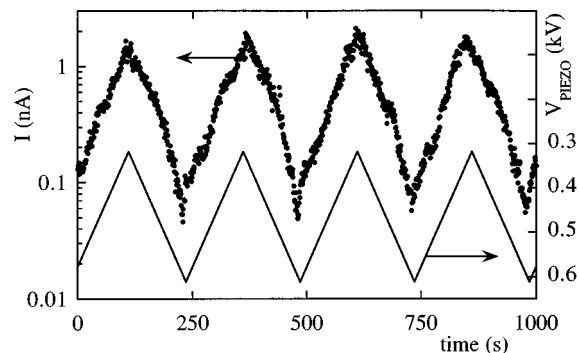

FIG. 3. The piezo voltage is changed in a triangular way (lower curve). The almost linear behavior of the tunnel current on a logarithmic scale reflects the exponential dependence on electrode separation. Note the large time scale, indicating the long term stability of the junction.

num films as a mask to etch through the SiO_2 into the Si with a CF_4/O_2 plasma [Fig. 1(b)]. The aluminum is then removed using a standard wet etch. The last step is a wet etch of the exposed Si area using a pyrocatechol-ethylene-diamine mixture.[4] Since the two cantilevers are aligned with the $\langle 110 \rangle$ direction in the substrate, a triangular pit is etched into the silicon, bounded by the SiO_2 edges and the $\langle 111 \rangle$ surfaces. Rapid undercutting at the convex corners by this etchant assures that the two cantilevers are free standing after the etching process.[5] The final device consists of two small cantilever beams (2.5μm long, 4 μm wide) connected with a 100 nm wide wire over a length L_{eff} [Fig. 1(c)].

The device is mounted against two counter supports, approximately 20 mm apart, in a break junction configuration.[3] A force is exerted on the backside via the piezo element which is moved towards the device using a course adjustment screw [Fig. 1(d)]. The silicon beam is strained, resulting in an elongation of the top layer. The elongation of u is concentrated on L_{eff}, resulting in the fracture of the gold wire while the Si substrate stays intact (even though gold is more ductile than silicon). The piezo element has a maximum elongation of 5 μm and is used for fine adjustment of either atomic size contacts or vacuum barrier tunnel junctions between the fractured gold electrodes. Figure 2 shows a

SEM photograph of a device before the bridging wire is broken. A 100 nm wire bridging the two cantilevers can be seen, and a slight undercut of the gold is visible. The etched pit into the Si [Fig. 2(a)] is bounded by a relatively rough SiO_2 edge, caused by the photolithography step. Some of the undercut below the SiO_2 layer results from this roughness and enlarges u to about 10 μm.

Experiments are performed at room temperature in a vacuum system (10^{-7}Torr) which uses an oil-free absorption/ion-pump combination in order to reduce contamination of the exposed electrodes with hydrocarbons. Figure 3 illustrates the long term stability and the exponential dependence of the tunnel current I_t on the vacuum barrier gap distance of this device. The junction is biased at 100 mV while a triangular voltage wave is applied to the piezo element (lower curve in Fig. 3). The variation in the piezo length induces a variation in the gap distance resulting in a change of the tunnel resistance (top curve in Fig. 3). The exponential dependence of I_t on the gap distance s is given by $I_t \propto \exp{-\alpha\sqrt{\Phi}s}$ with $\alpha = 1.025$Å^{-1}eV$^{-1/2}$ and Φ is the work function of the gold electrodes. As the electrodes are displaced over about 2 Å the tunnel current changes over almost two orders of magnitude. The reason for this exceptional stability is the smallness of u which determines the reduction factor r (the ratio between the piezo elongation and the induced electrode separation). For our devices we estimate $r \simeq 5 \times 10^4$.[3] From two devices we experimentally infer, from the known piezo elongation and assuming an exponential dependence of the tunnel current with $\Phi = 4$ eV, $r \simeq 10^4$. The discrepancy of a factor of five may be due to nonuniform strain near the etched pit. In the tunnel regime the current noise amplitude, which depends on the tunnel resistance, is determined at a 100 mV bias for tunnel resistances between 100 kΩ and 10 MΩ in a 1 kHz bandwidth. In this resistance range the experimental value for the current noise amplitude implies about 3 pm fluctuations in the tunnel gap distance. Although we do not know the exact origin of these fluctuations, a detailed noise analysis should include the thermal agitation of the cantilever.[6]

When the electrodes are brought close enough together, a contact is formed. Experiments performed in the contact regime are done in the following way: the contact is reduced

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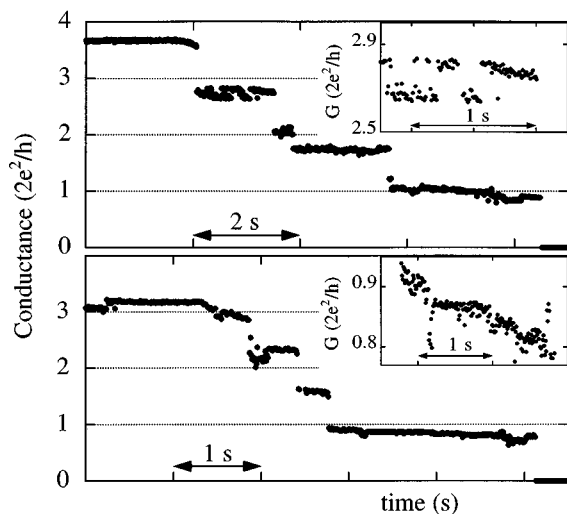
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FIG. 4. Two conductance traces recorded when an atomic scale contact reduces its cross section as a function of time. Conductance plateaus are found to be near integer multiples of $2e^2/h$, reflecting the conduction through single channels. The insets show two types of intrinsic noise present in the contact regime.

in size by increasing the piezo voltage until the conductance of the contact is approximately 10 times $2e^2/h$. Then the piezo voltage is fixed, and it is found that the contact relaxes by itself, until eventually a jump to the tunnel regime takes place. Before this jump occurs, the two electrodes may be bridged by a single atom. We tentatively attribute this effect to outdiffusion of atoms, thus decreasing the constriction size. The junction is biased at 26 mV and the current is measured with a sample rate of 100 Hz. Typically the conductance decreases discontinuously as a function of time. Many conductance traces show plateaus near integer multiples of $2e^2/h$, and often the last plateau in the contact regime is near $2e^2/h$ (Fig. 4). After this smallest possible contact, the jump to the tunnel regime results in almost zero conductance (vacuum tunneling only). Upon close inspection, it is seen that the majority of the plateaus are not at exact integers. Backscattering in these metallic point contacts may be responsible for these observations.[7] The description in terms of conductance channels is still valid, although with transmission coefficients slightly different from one or zero.

Conductance noise is clearly present on the plateaus in Fig. 4. This noise is not due to external disturbances and its amplitude is much larger than the measurement accuracy. In general, two different types of noise can be present. The switching of one or a few atoms between energetically equifavorable positions in the contact region can result in closely spaced conductance levels (inset in upper panel of Fig. 4). The high kinetic energy of the atoms at room temperature can drive them between various sites, thus influencing the conductance. Another type of noise has a more random nature (inset in lower panel of Fig. 4). This may be due to small strain variations and small out-of-equilibrium displacements (small compared to the lattice constant) of a group of atoms comprising the contact.

In conclusion, we have presented a new type of displacement transducer, which is inherently stable. We have shown the operation of this device with gold electrodes as well in the contact as in the tunnel regime. The device was shown to be sensitive to positional changes of a single atom.

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